Lake Chapala change detection using time series

Alejandra López-Caloca*[a], Felipe-Omar Tapia-Silva[a], Boris Escalante-Ramírez [b]

[a]Centro de Investigación en Geografía y Geomática Ing. Jorge L. Tamayo, Contoy 137, Lomas de Padierna, México, D.F., 14240.
[b] Universidad Nacional Autónoma de México, Facultad de Ingeniería, Cd. Universitaria, México, D.F., 04510.

ABSTRACT

The Lake Chapala is the largest natural lake in Mexico. It presents a hydrological imbalance problem caused by diminishing intakes from the Lerma River, pollution from said volumes, native vegetation and solid waste. This article presents a study that allows us to determine with high precision the extent of the affectation in both extension and volume reduction of the Lake Chapala in the period going from 1990 to 2007. Through satellite images this above-mentioned period was monitored. Image segmentation was achieved through a Markov Random Field model, extending the application towards edge detection. This allows adequately defining the lake's limits as well as determining new zones within the lake, both changes pertaining the Lake Chapala. Detected changes are related to a hydrological balance study based on measuring variables such as storage volumes, evapotranspiration and water balance. Results show that the changes in the Lake Chapala establish frail conditions which pose a future risk situation. Rehabilitation of the lake requires a hydrologic balance in its banks and aquifers.

Keywords: Lake Chapala, image segmentation, change detection, hydrologic balance, Markov random fields

1. INTRODUCTION

Remote sensing (RS) is a powerful technique for surveying, mapping and monitoring the Earth's resources such as lakes. This technique has become indispensable and increasingly more meaningful over large area rendering. The lake system constitutes a valuable natural resource, and it is an important expression of the hydrologic cycle. Additionally, the natural variability of its physical, chemical, and biological properties, defines different habitat conditions for its biodiversity. Morphometry (shape, depth, size), hydrology (water budget, flow rate or retention time), and in-lake spatial variability (horizontally and vertically) are important determinants of lake dynamics. In this paper we present, as a case of study, the Lake Chapala, whose properties have widely varied, in depth and in time- all over many different spatial and time scales. The adverse conditions in the Lake Chapala are diverse: drying out with the purpose of obtaining agricultural land, water extraction for agricultural and urban use, drought times, and pollution due to industrial-municipal effluents being some of them. Also, a considerable population exists around the lake which takes advantage of some its resources. An example of this impact can be found in the Cybercartographic Atlas of Lake Chapala[1].

The hydrologic problem, as expressed by variables such as average depth, inflow and outflow from rivers and water loss through evaporation and water intakes, has been extensively documented[2] . Filonov et al. (2001)[3] observed that the lake has suffered two extreme water level reductions: from 1945 to 1955 the annual average water level decreased by four meters and from 1977 to 1998 the level decreased again by five meters. The period of low water levels corresponding to the mid 50s, was associated to a climatic situation of extreme drought in the Lerma–Chapala basin[4, 5]. The period in the late 20th century was associated to an increase in water extraction for the city of Guadalajara's water supply.

Two periods of water inflows from the Lerma river were reported[6]: the first from 1934 to 1978 in which this variable increased in average to 1873 Mm^3yr^{-1}. The other identified period was from 1979 to 2003, where the average input was of only 425 Mm^3yr^{-1}, meaning a high inflow reduction from the previous years. A correlation between rainfall and its volume of 0.6 was found until 1978; afterwards the correlation was no longer clear and it was argued that the system appeared to have been severely perturbed. The low water level (after 1978) was associated to a reduced inflow from the Lerma river, explained by excessive water extraction upstream of the Lerma river basin

* alopez@centrogeo.org.mx; phone 26152289,ext. 232

The inflow from the Lerma river is relatively small[7] (approx. 270 Mm^{3}yr^{-1}) compared to other water sources such as precipitation in the lake (approx. 710 Mm^{3}yr^{-1}) or contributions from the lake's own watershed (Mm^{3}yr^{-1}).

Evaporation (approx. 1400 Mm^{3}yr^{-1}) is considered an important factor to water loss from the lake considering its big area of approximately 700 km^2. The estimated amount of water lost through rivers and pumping is 272 Mm^{3}yr^{-1} and it is considered that all the above mentioned elements of the hydrological balance result in a difference of inputs and outputs at a loss of 504 Mm^{3}yr^{-1} a year. The diminishing water contribution from the Lerma river in recent years was due to overuse in the basin and to continuous water extraction in order to supply the city of Guadalajara, which has reduced the average depth of the lake to about 50 percent of the long term average[8]. Another model of the hydrologic system[9, 10] observes that precipitation and inflows from the Lerma river are the main water inputs while evaporation and intakes for urban consumption as well as outflows (Grande –Santigo rivers) are the main output sources.

Due to all these severe dimension changes of the Lake Chapala it is of great interest to study its processes by means of RS information extraction.

Several methods of figure extraction for open water bodies exist with RS data. Those that are based on multispectral properties, are: water indices[11], variants of principal component analysis (PCA)[12], processing chain for retrieved and representation shapes[13] and mathematical morphology [14].

In this paper, we present a methodology obtained from remote sensing data, to establish shoreline areas in the Lake Chapala. The approach is based on an evaluation of the NDWI index and Markov Random Field (MRF) segmentation. The results of segmentation (area, perimeter) are related to volume levels and evaporation data. The Lake Chapala study considers from 1990 to 2007 with satellite images and from 1934 to 2002 with statistical data obtained by field measurements. Timely and accurate change detection of the Lake Chapala will provide the foundation for a better understanding of the relationship and interaction between human and natural phenomena to better manage and use its resources in the future (eg. Managing irrigation and forescasting crop production).

2. REVIEW OF WATER INDEX AND SEGMENTATION

Several studies on the separation of a body of water in a satellite image are supported on the determination of the water indices. At an early stage, the NDWI (Normalized Difference Water Index), was used to determine humidity levels in the vegetation[15]. This index was defined as: (NIR-MIR)/(NIR+MIR). Later on, it was reformulated in order to enhance bodies of water[11] as (Green-NIR)/(Green+NIR). The result from this index in a body of water presents positive values whereas on the ground or vegetation, it presents zero or negative values. However, the task of separating a body of water becomes a lot more difficult when vegetation (water lilies, algae) or suspended sediments are present[16]. Comparisons in segmentations between one from an NDWI and one from multispectral images through a PCA variant[12] show that there are differences in the shoreline due to sediments suspended in the water.

In an attempt to enhance the digital values in bodies of water, other indices, such as the MNDWI, have been proposed, this last one having as an objective to achieve a higher definition[17] based on the green and middle infrared bands: (Green-MIR)/(Green+MIR), making the contrast better between water and land.

The purpose of this work is to test a segmentation process based on Markov's random fields (a.k.a. MRF) and to apply it directly to the NDWI in order to segment water from vegetation in the lake.

The MRF has the advantage of segmenting an image into mutually excluding regions, each one having uniform and homogenous properties, whose values are significantly different from those in the neighboring regions. This type of segmentation is helpful in cases where vegetation is present within the lake. The determination of vegetation in the lake is indicative of the chemical conditions of itself, since it favors the growth of vegetation and, if not controlled, a possible factor for drying out; besides, these vegetation areas do not permit the lake's water's volume to be adequately determined if it is not taken into consideration.

Most of the algorithms only take into consideration the lakes' shorelines and do not consider the vegetation's segmentation (water lilies and others), which represent transition stages in a body of water's health. Some of these new structures (vegetation, sediments and mud banks) are indicators of a possible lake dry out.

2.1 Markov random field segmentation in a lake

There have been reports on several models of segmentation based on MFR, as is the SAR segmentation of images[18, 19]. However, it has never been applied to lake segmentation.

Markov's random fields are part of the Probability Theory, being a tool to analyze spatial or contextual dependencies. MRF is formulated within the Bayesian framework. The optimal solution is stated as the maximum a posteriori probability (MAP) estimation. The problem may be considered as labeling using restrictions that consider a priori knowledge and to observations. Labeling is the process assigning labels to the image's pixels. In this case, the optimal solution is defined by labeling, through a MAP criterion, and is calculated by minimizing the a posteriori pixel energy. The a posteriori probability is defined by the Bayes rule, based on an a priori model and a probability model (Pott model). The probability model is linked to the way the data is observed and the a priori model depends on how certain a priori restrictions are expressed. The MRF process may be summarized in 3 steps:

 a) Initial segmentation: Pose the problem as assigning labels to the image's pixels, being this labeling configuration a proposed solution.

b) Parameter estimation: Present a label based on the Bayesian rule, the optimal solution being defined as a MAP labeling configuration; use Gibbs model to characterize the a priori distribution in the labeling configuration; and define the Gibbs' energy function.

c) Energy function minimization: use an algorithm to minimize the Gibbs energy distribution function such as Simulated Annealing algorithm, therefore obtaining the MAP labeling configuration.

The Simulated Annealing, allows to solve the estimation problem according to the MAP criterion by looking for convergence towards the global minimum of the a posteriori energy function. It was considered that the conditional probability of a determined site having a specific type of grey level, given the values of all remaining sites in the image, was identical to the conditional probability given the field's values in a small set of sites, meaning its neighborhood.

On the NDWI image several training data was defined in order to characterize the media of the classes defined in Section 3. The joint energy functions $U(X|Y)$ are given by the cost functions defined by Descombes,

3. METHODOLOGY

The study area of the Lake Chapala belongs to the The Río Lerma watershed (Fig.1), which is characterized for having a subtropical climate ranging from sub-humid to arid. In this watershed, as well as in central and southern Mexico, there is a well-defined rainy season from June to October. The variation of mean precipitation in the watershed ranges from 300 to 1000-1200 mm and the surface evaporation accounts for almost twice the average rainfall[20].

The LakeChapala is located in the following corner coordinates: longitude W103° 50', latitude N21° 00'; longitude W102° 20', latitude N21° 00'; longitude W102° 20', latitude N19° 50'; longitude W103° 50', latitude N19° 50'. It stands on the border between the states of Jalisco and Michoacan. It is fed by the Lerma, Zula, Huaracha and Duero rivers and (outflows) drained by Santiago river. The lake also contains three small islands (Chapala Mescala and Alacranes).

In this study, several data from different sensors are used, which were acquired in the following dates: 02/11/1973, Landsat MSS, 03/20/1976 Landsat MSS, 03/12/1986 Landsat MSS, 03/07/1990 Landsat 7 TM, 04/21/1992 Landsat MSS, 10/17/1996 Landsat 5, 03/11/1999 Landsat 7 TM, 03/09/2001 Landsat 7 ETM+, 06/02/2007 Landsat 7 ETM+, 12/15/2003, 12/14/2004, 11/02/2005, 12/12/05, 12/29/05 de SPOT 4 HRG-2.

Each image was geo-referenced to the Transverse Mercator and Datum WGS84 projection system with orto-images of 20m in spatial resolution corresponding to the study area, and adjusted to a 20m pixel size. Additionally, a transformation to reflectance values was made as well as the atmospheric effects correction.

With the objective of establishing cause-effect relationships between the hydrologic parameters measured in the 1934 – 2002 period and the data obtained from satellite images, data shown on Table 1 was collected. This table includes the annual parameters analyzed as well as the methods used to obtain them and the information source. The sampling period is 1934-2002.
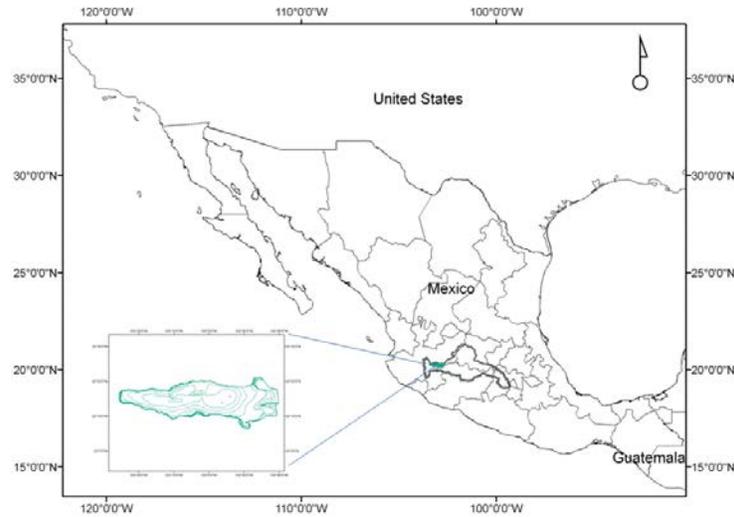
Fig. 1. Location of the Lake Chapala and Río Lerma Watershed (in bold) which is the main water source of the lake.

Table 1. Parameters and sources for hydrological data.

Parameter	Expressed by
Lake level (Minimum, maximum and average obtained between minimum and maximum value)	Relative elevation (maximal value is 100 m, representing a real elevation of 1526.8 above sea level[5,a]
Lake volume (at the end of the year)	Area-elevation-volume curve[b,c,*]
Evaporation	Pan evaporation measured in a Station located at the edge of the lake[b]
Net inflow from rivers	Annual Inflow from rivers minus annual outflow through rivers[b]
Rainfall	Rainfall measured in a station located at the edge of the lake[b]
Water extraction	Water extracted from the lake for domestic, municipal, agricultural and industrial uses[b]

Sources: [a]CEAJ.- Jalisco's state water commission (Comision Estatal del Agua de Jalisco); [b]CNA[21].- Comisión Nacional del Agua, IMTA.-Instituto Mexicano de Tecnología del Agua. 2000; [c]SARH Secretaria de Agricultura y Recursos Hidraulicos, 1981[22];* The parameter lake's water volume is determined using an area-elevation-volume curve[3] meaning that the value that is actually measured to evaluate the water volume is relative elevation (lake depth).

4. EXPERIMENTAL RESULTS.

4.1 Remote Sensing Analysis

Image segmentation was made for the 1973 -2007 period, considering 4 classes: Class1: water, Class2: water/water sediments/shallow water, Class3: water/vegetation, Class 4: land for the NDWI and MNDWI segmentation through MRF. Fig. 2 shows the segmentation results. It can be noticed that the periods of greater fluctuation were in 1990 and 2001. Data are represented through bitmaps: The obtained result from this segmentation was a bitmap for each date. Based on these bitmaps, the lake morphometry data was also calculated. Morphometry defines a lake's physical dimensions and measures the lake basin shape. These parameters were area (A), shoreline length (L), form factor, roundness, maximum width (maxwidth) and maximum length (maxlength) (Fig. 3). It can be noticed that the periods of greater fluctuation were in 1990 and 2001 for all the parameter calculated. It can be noticed that the periods of greater fluctuation were in 1990 and 2001 for all the parameters calculated. Percentage was estimated with water/vegetation area as compared to the total lake area: 2.5% (03-12-1986); 12.21% 21-04-1992); 6.78% (03-11-1999), 0.18% (03-09-2001), 12.32% (14-03-2004), 4.89% (12-12-2005), 0.04% (06/02/2007).
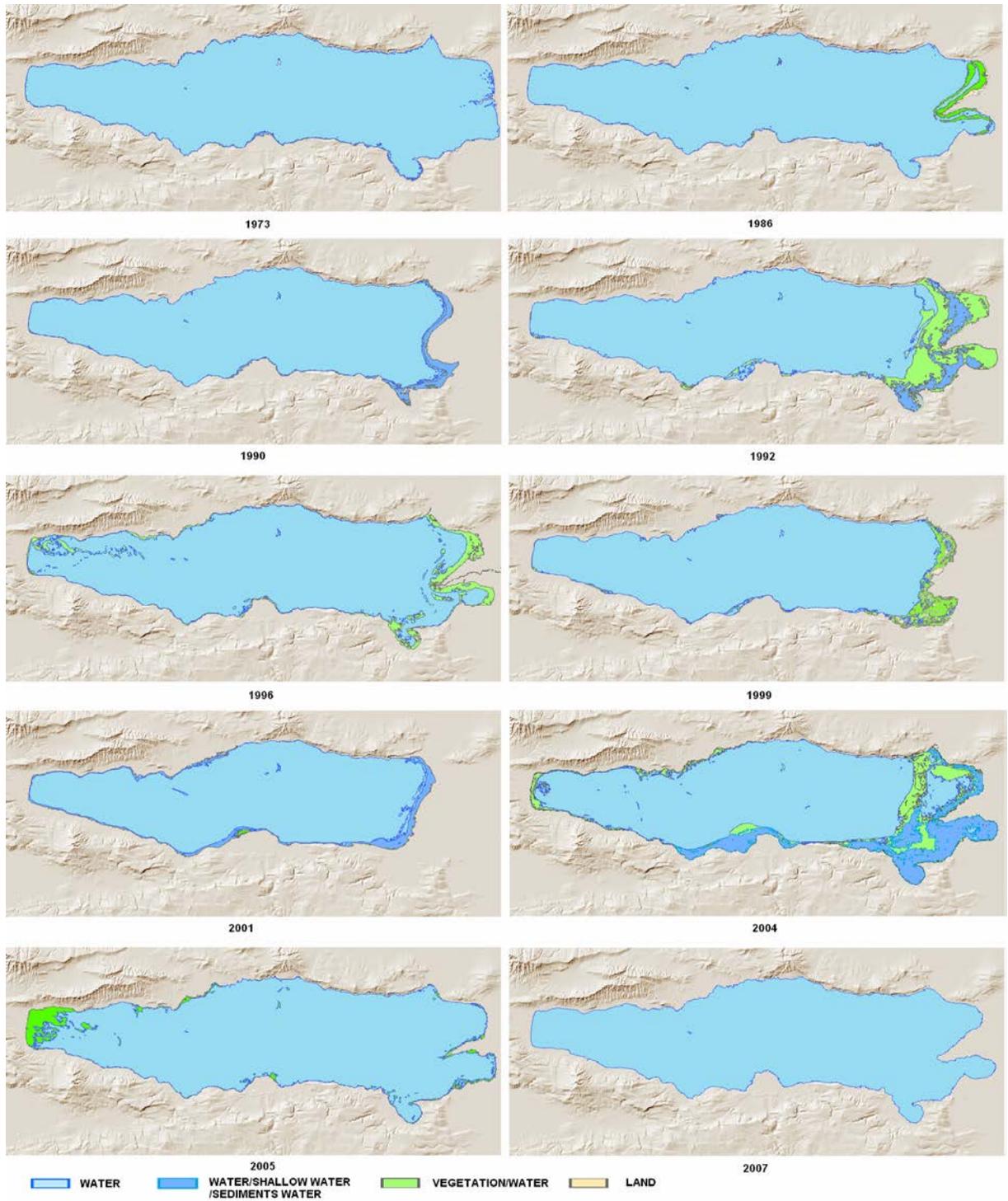
4

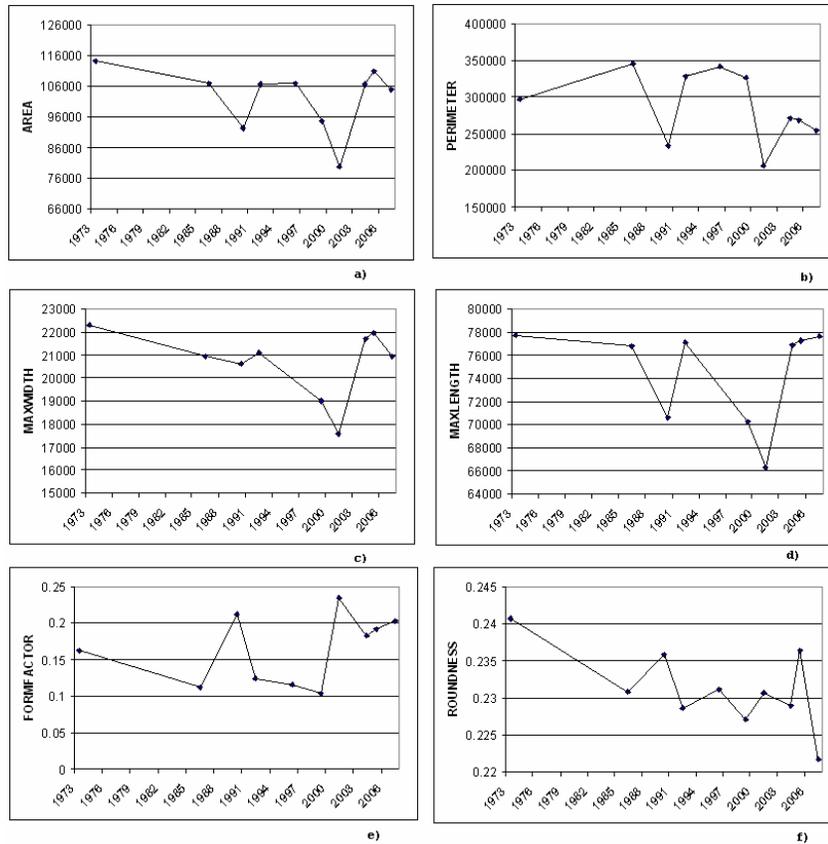Fig.2. Bitmap obtained of MRF segmentation

Fig 3. a) The lake area, considering the addition of Class1, Class 2, Class 3, the island's polygon area not included, b) Shoreline length (circumference/ perimeter of lake), is expressed including all shoreline lengths. c) Maximum length is the distance, in a straight line, between the two farthest points on a lake. The distance was measured without intersecting a land mass. d) Maximum width is the maximum distance between the two widest points of a lake, the distance was measured at a 90° angle to the maximum length. e) The descriptor for form factor[23] is one of the most commonly used, giving an idea of how irregular is its outline. f) Roundness[23] is similar to form factor, but instead of considering the perimeter, the max length of the figure is considered. g) Percentage was estimated with water/vegetation area as compared to the total lake area.

4.2 Statistic Hydrologic Analysis

The lake's volume and depth analysis was made with univariate and multivariate regression analyses. At a first stage, the period of the statistical analysis from 1934-2002 was taken into consideration. In order to find statistical discrepancies, and based on the results reported by De Anda et al 2005, this period was split into two: 1934-1978 and 1979-2002, which were separately analyzed.

The dependent variables are: lake levels (minimum, maximum, average) in the year and lake's water volume at the end of the year. Two main kinds of independent variables (predictor terms) are included: climatic, measured locally, and indicating context variables. Rainfall and evaporation are included in the first group, while net inflow from rivers is included in the second one and is an indicator of the hydrologic function of the Lerma basin. Its fluctuations are normally explained by processes which take place outside the lake, in the basin (rainfall, evaporation, runoff and water extraction for human use). The other variable included in the context group is water intake for human use. This variable accounts for the influence of the human settlements at the lake's region.

Lake level and volume (variables of interest) are fluctuating parameters. Figure 4 shows the time series (line) for the hydrologic parameters obtained through field measurements at the Lake Chapala. Around 1950[5, 4] it is possible to notice a minimum of lake levels and water volume. Other minimums of these variables took place from 1989 to 1990 and from

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1999 to 2000. The rainfall and evaporation variables show a stable behavior in the analyzed time. For all analyzed periods, they appear to be more related to the variables of interest.

The results of the univariate and multivariate regression analyses (Table 2a,2b), discussed in the following paragraphs, will indicate which variables are actually correlated to the variables of interest.
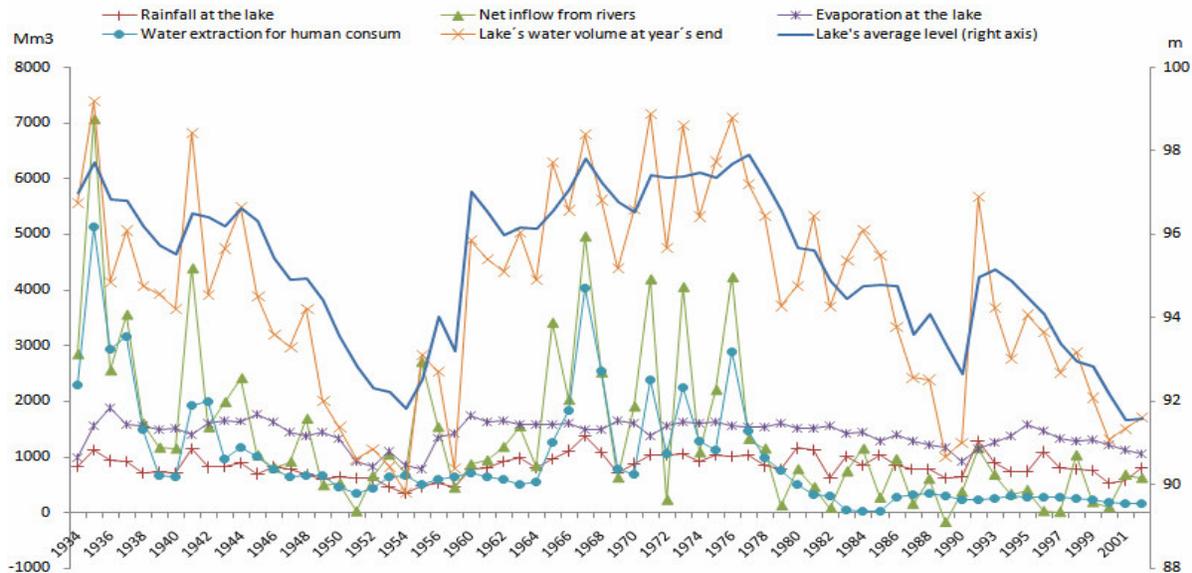

Fig.4. Times series of measured hydrologic parameters of Lake Chapala (1934-2002)

Table 2a.- Univariate and multivariate regression analyses

Dependent variables (Y)	Multivariate regression Best Model $Y= a + b_1X_1 + b_2X_2 + b_2X_3 + b_4X_4$	R^2	RMSE
1934-2002			
MinLY	$Y = 86.6 + 0.002X_1 - 0.0003X_2 + 0.004X_3 + 0.0008X_4$	0.77	0.86
MaxLY	$Y = 87.38 + 0.0027X_1 + 0.00061X_2 + 0.0038X_3$	0.81	0.86
AveLY	$Y = 87.07 + 0.0025X_1 + 0.0038X_3 + 0.0006X_4$	0.78	0.83
LWVolEY	$Y = 87.38 + 0.0027X_1 + 0.00061X_2 + 0.0038X_3$	0.85	671
1934-1979			
MinLY	$Y = 87.23 + 0.0036X_1 + 0.0034X_3$	0.78	0.76
MaxLY	$Y = 88.4 + 0.005X_1 + 0.0003X_2 + 0.0024X_3$	0.87	0.70
AveLY	$Y = 87.7 + 0.005X_1 + 0.003X_3$	0.84	0.67
LWVolEY	$Y = -3106 + 5.38X_1 + 0.7X_2 + 1.63X_3 - 0.54X_4$	0.88	675
1979-2002			
MinLY	$Y = 85.4 + 0.002X_1 + 0.005X_3$	0.62	0.86
MaxLY	$Y = 86.3 + 0.0031X_1 + 0.0042X_3$	0.64	0.86
AveLY	$Y = 85.92 + 0.0026X_1 + 0.0045X_3$	0.65	0.80
LWVolEY	$Y = -4809 + 3.78X_1 + 1.01X_2 + 3.27X_3$	0.82	600

MinLY.-Minimum levels in the year; MaxLY.-Maximum levels in the year; AveLY.- Average Levels in the year ; LWVolEY.-lake's water volume at the end of the year.

Dependent variables Y)	Univariate regression (s. definition of independent variables below)							
	Y =f(X1) Rainfall		Y=f(X2) Net inflow		Y=f(X3) Evaporation		Y=f(X4)Water extraction	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
1934-2002								
MinLY	Y = 90.53 + 0.005X1		Y = 93.95 + 0.0005X2		Y = 86.7 + 0.0056X3		93.72 + 0.00095X4	
	0.36	1.38	0.16	1.6	0.62	1.07	0.3	1.45
MaxLY	Y = 90.42 + 0.0065X1		Y = 94.53 + 0.00095X2		Y = 87.9 + 0.0056X3		Y = 94.53 + 0.0014X4	
	0.48	1.42	0.45	1.46	0.47	1.43	0.48	1.42
AveLY	Y = 90.48 + 0.00576X1		Y = 94.24 + 0.00072X2		Y = 87.3 + 0.056X3		Y = 94.13 + 0.00116X4	
	0.44	1.36	0.3	1.51	0.56	1.2	0.4	1.4
LWVol EY	Y = -1827.77 + 6.95X1		Y = 2650.67 + 0.915X2		Y = -2227.21 + 4.37X3		Y = 2843.97 + 1.118X4	
	0.65	1074	0.5	1281	0.35	1472	0.38	1427
1934-1979								
MinLY	Y = 90.5 + 0.006X1		Y = 94.7 + 0.00003		Y = 87.86 + 0.005X3		Y = 94.3 + 0.0007X4	
	0.58	1.07	0.07	1.6	0.62	1.01	0.2	1.5
MaxLY	Y = 90.22 + 0.0077X1		Y = 95.04 + 0.0008X2		Y = 89.5 + 0.005X3		Y = 95.01 + 0.0011X4	
	0.79	0.87	0.4	1.5	0.43	1.43	0.42	1.45
AveLY	Y = 90.3 + 0.0067X1		Y = 94.95 + 0.0005X2		Y = 88.66 + 0.005X3		Y = 94.63 + 0.0009X4	
	0.72	0.9	0.18	1.56	0.56	1.14	0.33	1.4
LWVol EY	Y = -1948.3 + 7.67X1		Y = 2644 + 0.886X2		Y = -982 + 3.67X3		Y = 2933.6 + 1.09X4	
	0.76	915	0.52	1318	0.25	1644	0.37	1508
1979-2002								
MinLY	Y = 91.01 + 0.003X1		Statiscally not significant		Y = 86.37 + 0.0054X3		Y = 92.34 + 0.0043X4	
	0.18	1.23			0.54	0.93	0.22	1.2
MaxLY	Y = 91.13 + 0.004X1		Statiscally not significant		Y = 88.3 + 0.005X3		Y = 93.58 + 0.0036	
	0.35	1.1			0.41	1.05	0.15	1.26
AveLY	Y = 91.07 + 0.0035X1		Statiscally not significant		Y = 87.34 + 0.0051X3		Y = 92.97 + 0.004X4	
	0.27	1.31			0.5	0.94	0.2	1.19
LWVol EY	Y = -1387.3 + 5.47X1		Y = 2488.5 + 1.37X2		Y = -1442.6 + 3.53X3		Statiscally not significant	
	0.63	839	0.24	1200	0.22	1215		

MinLY.-Minimum levels in the year; MaxLY.-Maximum levels in the year; AveLY.-Average Levels in the year; LWVolEY.-lake's water volume at the end of the year.

5. DISCUSSION

5.1 Lake levels as dependent variables

In the case of the lake levels (minimum, maximum, average) in the year, taking into account all data from 1934 to 2002 (full period); for dependent variables, evaporation explains from 47% to 62% of the variance. Evaporation is therefore the most important variable that explains the variations of the lake levels for this analyzed period. Considering that rainfall at the lake explains from 36% to 48% of the variance, it is the second most important variable. This observation indicates that the variation of lake levels in the time period 1934-2002 is basically influenced by climatic factors measured locally at the lake. The resulting multivariate explains, in this case, 77% of the variance and includes all the analyzed independent variables.

In the case of lake levels (minimum, maximum and average) in the year, during the period from 1934 to 1979 (first split period); for dependent variables, rainfall is the predictor that explains the highest percentage of the variance (from 58%

to 79%). Taking into account that evaporation explains from 43% to 62% of the variance, it is the second most important independent variable. These results suggest that for this time period, lake levels are basically determined by climatic factors, measured locally. In case of the multivariate regression analysis, two of the best models include only rainfall and evaporation accounting for 78% to 84% of the variance of the lake levels.

The obtained results for 1979 to 2002 (second split period) are not so different from the results described in the previous paragraphs. Local evaporation is the variable that explains the highest percentage of the variance lake levels (from 41% to 54%) followed by rainfall which explains from 18% to 35%. A sensible reduction of inflow from rivers can be observed in this period[6]. However this parameter, as an independent variable, does not influence the variance of lake levels at all. This result can indicate that the regional processes occurred in the Lerma basin from 1979 to 2002 do not influence in a statistically significant way the lake levels. The best models resulting from the multivariate regressions included again, as significant predictor terms, rainfall and evaporation, again indicating that the local climatic conditions are the most determinant factors that explain the analyzed dependent variables. The best regression models obtained a lower correlation coefficient (0.62-0.65) when compared to the previously analyzed time periods (0.77-0.87). This observation suggests that there is another predictor term not included in the performed analyses that could account for an important percentage of the dependent variable's variance. This term can probably be related to the effects of the groundwater changes in the region of the Lake Chapala. Unfortunately there is no adequate knowledge of the ground water behavior of the region[5].

For all time periods no significant difference was observed in using minimum, maximum or average lake levels as an independent variable. However, it was observed that the average lake level obtained normal correlation coefficients near the medium value of the correlation coefficient of the minimum and the maximum lake levels.

5.2 Lake volume as a dependent variable

Lake volume is actually not measured but obtained with the elevation-volume curve[22] using lake level (elevation) as input. Its relationship with the predictor terms are described in the following paragraphs.

For the time period from 1934 to 2002, considering lake's water volume at year's end as a dependent variable, the predictor term with the highest correlation coefficient was rainfall. This term explains 65% of the variance. The predictor term with the second highest correlation coefficient is net inflow from rivers. For this time period it can be observed that one local climatic variable (rainfall) and one context variable (net inflow from rivers) have the strongest influence to define the variability of water volume at year's end. The obtained multivariate regression equation includes, as predictor terms rainfall, net inflow from rivers and evaporation. Its corresponding correlation coefficient defines that the obtained model accounts for 85% of the variance.

In the period from 1934 to 1979 results indicate a similar behavior of the dependent variable in the lake's water volume at year's end. Rainfall accounts for 76% of the variance, indicating that for this period, the lake's water volume depends basically on this climatic parameter. Once more a local climatic variable (rainfall) is the most influencing predictor term. As in the previously analyzed case, the second highest predictor term is net inflow from rivers with a 0.5 correlation coefficient. The obtained multivariate regression model accounts for 88% of the variance of the dependent variable and includes all independent variables.

For the period from 1979 to 2002 rainfall is again the predictor term with the highest explanatory capacity for the variance in the lake's water volume (63%). At other times, the net inflow from rivers is the explanatory term with the second highest correlation coefficient. However, in this case, the capacity of evaporation that explains the variance is very close to net inflow from rivers. Therefore, for this period, the lake's water volume is determined by two local climatic variables and one context variable. These variables are included in the best obtained multivariate regression model which has the capacity to explain 82% of the variance.

5.3 Comparison in water volume determined through RS and through field observations

The variable, which could be obtained by using RS techniques, as previously seen, is lake volume. In order to do this, the area-elevation curves[22] were used by taking the area obtained with RS. The obtained volumes corresponding to the acquisition dates of the analyzed images were compared at a monthly basis to the values determined by measuring lake elevation.

A comparison of the water volume obtained through RS determinations with the volume determined through field measurements is shown in figure 3. The measured lake's water volumes are in average 15% lower in field measurements than the ones obtained using remote sensing techniques. This aspect should be confirmed using more images from other acquired dates. However, the results indicate that a correction factor (of around 15%) in the lake volumes obtained through both measurements must be considered to estimate with more precision the measured water volumes.
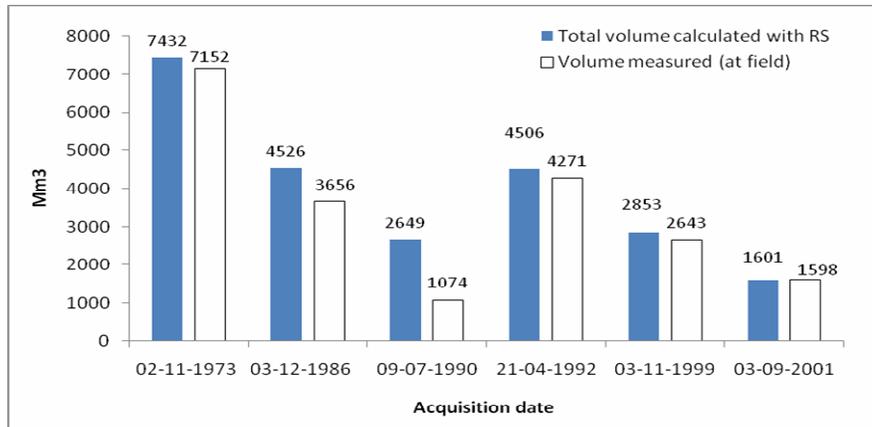

Figure 3. Comparison of water volume obtained with RS and field measured.

6. CONCLUSIONS

Evaporation measured at the lake, followed by rainfall, was the most important predictor that explains the variations of lake levels from 1934 to 2002. Rainfall, followed by evaporation, was the most important predictor that explains the variance of lake levels from 1934 to 1979. Evaporation, followed by rainfall, was once again the most important predictor of lake levels from 1979 to 2002. Therefore, the variation of lake levels in all analyzed periods is fundamentally influenced by climatic factors measured locally at the lake (rainfall and evaporation).

For the period 1979-2002 a remarkable reduction of net inflow from rivers can be observed. However, this variable is not significant to explain the variance of lake levels. For this reason the processes occurred in the Lerma basin seems not to influence in a statistically significant way the lake levels. For this time period, there is another predictor term not included in the performed analysis that could account for an important percentage (around 37%) of the variance of lake levels. This term could probably be groundwater, parameter which has been not investigated enough in the study zone.

In case of lake volumes, as a dependent variable, for all considered periods, one local climatic variable (rainfall) and one context variable (net inflow from rivers) had the strongest influence to define the variability of water volume at year's end. The best fit regression equations largely explain, in all cases, the variance of the dependent variable. The lake's water volume, determined by using field measurements, are in average 15% lower than the same values determined using RS. Therefore a correction factor can be proposed to adjust the measured values. The results show that the changes in the Lake Chapala establish frail conditions which talk of a future risk situation. The rehabilitation of the lake requires a hydrologic balance in its banks and aquifers.

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